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# SELF DEPLOYABLE GEOMETRIES FOR SPACE APPLICATIONS

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## ABSTRACT

The variable-geometry structures are useful in the aerospace applications because they cross of a compact configuration (launch phase) in a spread geometry (operational phase). Due to its expertise on the conception of light weight structures, the SIGECO team designs and realizes innovative structures: their advantage is to deploy automatically by storage of energy of flexion in flexible joints. A first study was led on a structure with scissors which conceive the skeleton of an auto-deployable satellite antenna. Following upon these works, the aim of this article is to propose the geometrical configuration of another kind of structure without articulations between elements (pivots, slide junctions). This structure form a circular plane or a three-dimensional structure (partially opened). The bar number is divided by two compared to the scissor. The applications concern auto-tensing structures as space antenna (LDR or other), desorbitation or solar sails and stiff structures for the support of solar panels.

## 1. SELF DEPLOYABLE STRUCTURES

The variable-geometry structures are useful in the aerospace applications of the fact they cross of a compact configuration (launch phase) in a spread geometry (operational phase). Many systems have been developed like inflatable solar sails [1] which consist on a tape boom deployment, conical V-fold bar ring with flexible pre-stressed center [2] for space antenna.

A new family has been developed by SIGECO research team, based on flexible joints enabling an automatic deployment [3]. In this paper, a new configuration is described offering other application.

### 1.1 Scissor structure

The use of flexible joints (junctions) permits to deploy a scissors structure automatically by storage of elastic energy in the connections. A model developed under

ANSYS® is able to simulate the deployment and to analyze mechanically the structure behavior (Fig.1).

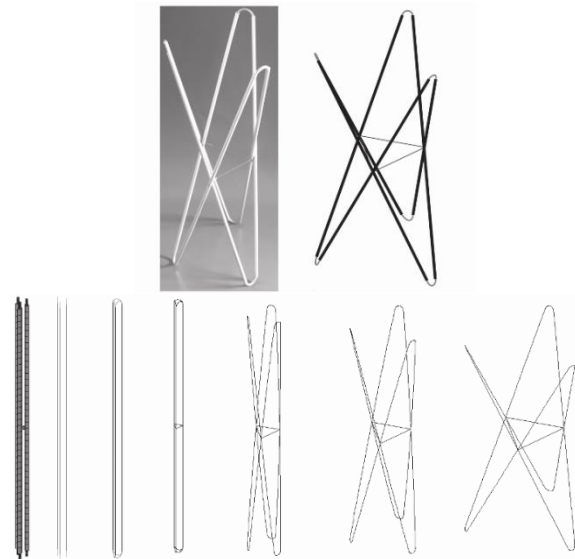


Figure 1 . Scissor deployment

By duplicating elements, it is possible to generate a circular structure which tight a network of cables and a tricot reflector for satellite dishes [4]. After numerical simulations (statics, dynamics, modal analysis), a prototype was realized by the research team to validate the concept (Fig.2).

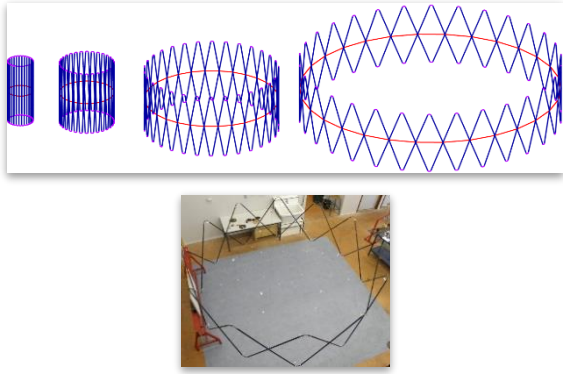


Figure 2 . Deployment of a structure made of scissors with flexible joints

### 1.2 A new configuration without articulation

To avoid articulation between elements (pivot, slide junction), we chose to develop a new solution based on the same principle of deployment (flexible connections). The basic module for this new configuration is constituted by 4 bars and 4 flexible connections (in purple – (Fig.3)). One of the interest of this new structure is that the deployment can be total (flat structure) or limited by additional elements (voluminous phase). The physical model presented consists on connected aluminum bars with flexible joints.

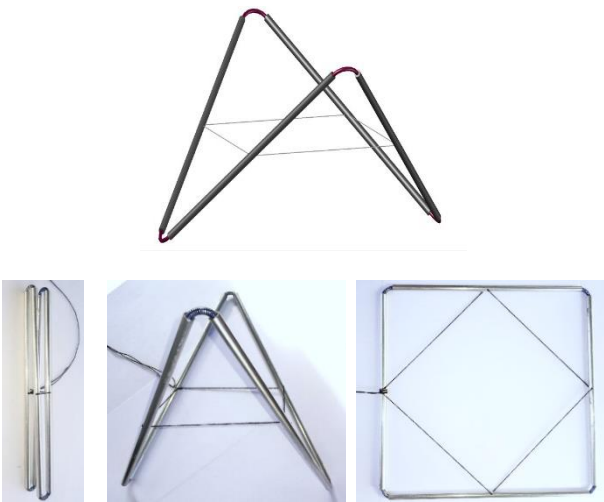


Figure 3 . Basic module – Phases of deployment

In the case of a volumic deployment, the juxtaposition of a basic element can generate stiff structures. For plane surfaces of basic elements, the multiplication of elements and connections can generate important surfaces by minimizing the initial dimensions.

## 2. GEOMETRY OF THE SYSTEM

According to the desired application, the structure can be adapted. Two solutions are presented:

- Simple volumic module, which is used to form a grid by repetition and juxtaposition, to create the support of a space antenna or solar panels.
- An outer ring structure for solar sails or space antenna applications. Adjustment of the number of bars allows optimizing the surface of deployment.

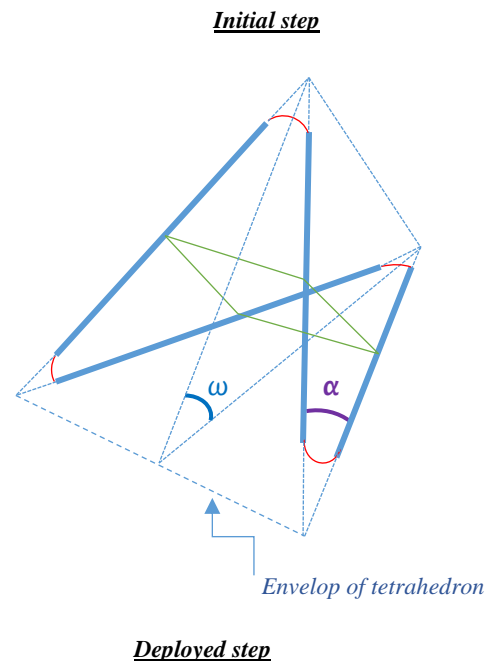
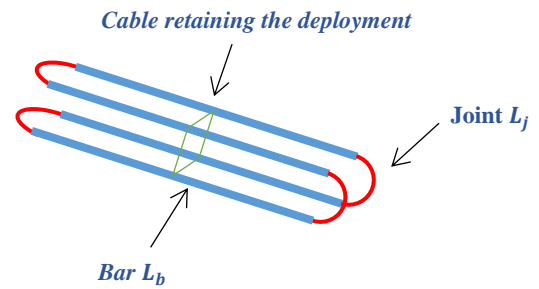


Figure 4 . Initial and last step ( $\omega$  fixed) of the deployment

## 2.1 Elementary module for volumic deployment

The elementary module is made of 4 bars and 4 joints (Fig.4). The parameters that give the geometry of the deployment are  $\alpha$  and  $\omega$ , where  $\alpha$  is the angle between two consecutive bars, and  $\omega$  the angle between the planes defined by the joints. The relation between  $\alpha$  and  $\omega$  is given by Eq.1:

$$\omega = 2 \arcsin \left( \tan \left( \frac{\alpha}{2} \right) \right) \quad (1)$$

Other parameters define the geometry:

- $L_b$  is the length of the bar,
- $L_{joint}$  is the developed length of the joint,
- $R_{init} = L_{joint}/\pi$  is the radius of joint in folded configuration.

In function of the aperture of the tetrahedron (parameter  $\alpha$  corresponding to the angle formed between two successive bars), it is possible to obtain either a volume (passing through up to a maximum of  $\alpha=66^\circ$ ), or a plane surface ( $\alpha=90^\circ$ ) (Fig.5). The calculated surfaces of volumes and surfaces are those of the enveloping tetrahedron. Indeed the volume of the structure is approximated by means of a frame according to the taking into consideration of the volume corresponding to the connection. Thus the volume writes:

$$V_E = \frac{2}{3} \sin^2 \left( \frac{\alpha}{2} \right) \sqrt{\cos(\alpha)} \left( \frac{2\pi}{(\pi-\alpha) \tan(\frac{\alpha}{2})} R_{init} + L_b \right)^3 \quad (2)$$

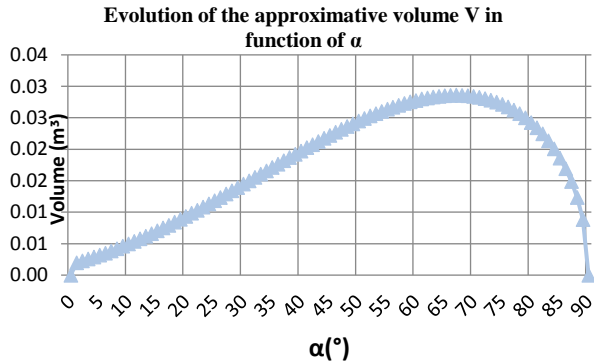


Figure 5 . Tetrahedron envelop volume with  $L_b = 0,5m$  and  $L_{joint} = 2,5cm$

In the aim to control the deployment, it is interesting to determine the angle of aperture according to the length of cables  $L_c$  (Fig.6) maintaining the module. The writing is made from the initial configuration to any aperture.

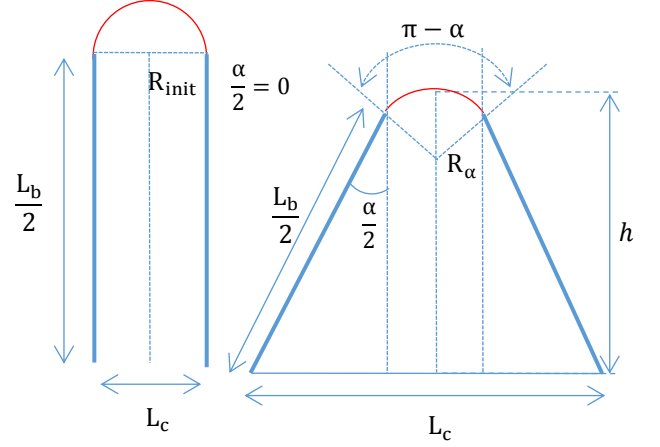


Figure 6 . View of the aperture of the structure

We define  $R_\alpha = \frac{\pi R_{init}}{\pi - \alpha}$  the radius of the circular arc in the deployed configuration. The length of the cable maintaining the module is obtained by Eq.3:

$$L_c = L_b \sin \left( \frac{\alpha}{2} \right) + 2R_\alpha \cos \left( \frac{\alpha}{2} \right) \quad (3)$$

The Fig.7 give  $L_c$  in function of  $\alpha$  showing a monotonic relation. The length depends only on the desired configuration.

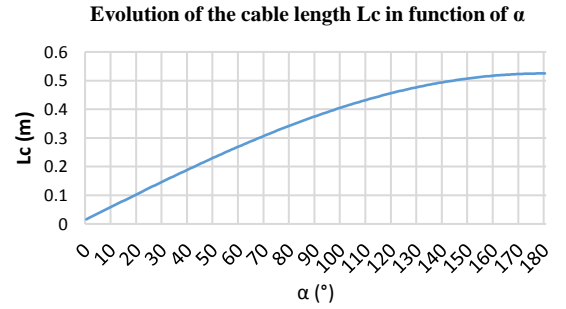


Figure 7 . Cable length in function of alpha

The assembly of several tetrahedrons form an auto-deployable structure which will be used as plan support for reflectors or solar panels (Fig.8).

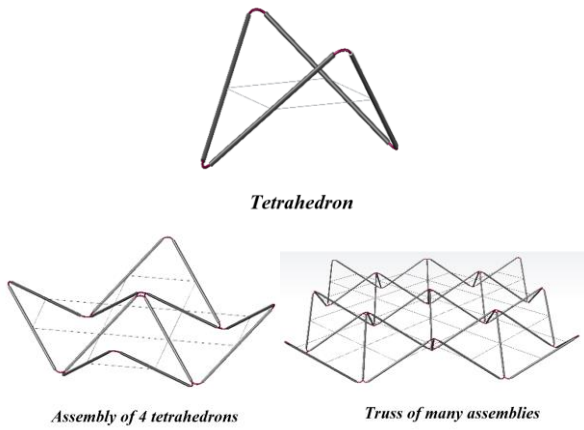


Figure 8 . Assembly of tetrahedrons

## 2.2 Ring geometry

In the same way as by lengthening the cable on the tetrahedron, we obtain finally a plan polygon square on the (Fig.4). By increasing the number of bars, we approach a quasi-circular shape (Fig.9). Using the same structural principle, but increasing the number of bar-joint sets (as represented in Fig.6), we can form a ring structure. It can even approach a circular shape with a high number of bars. A plane configuration, a regular polygon, can be formed as when  $\alpha = 90^\circ$  for the flat elementary module.

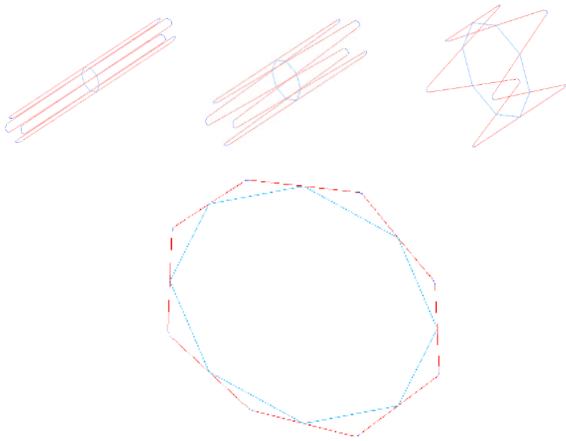


Figure 9 : Diverse steps of deployment for a n-bars structure

In the flat geometry, we propose the approximation of the necessary bars number  $N$  in function of the desired surface  $S_d$  in Eq.4.

$$N(\lambda) = \left\lceil \sqrt{\frac{2\pi}{\lambda} \left( 1 + \sqrt{1 + \frac{\lambda\pi}{3}} \right)} \right\rceil \quad (4)$$

where  $\lambda = \frac{L_b^2}{S_d}$  and  $\lceil x \rceil$  is the integer part of  $x$  rounded up to the superior unit.

To insure the folding, the number of bars to be assembled must be even and strictly upper than 2. So, when  $N$  is odd, one must consider the next even value  $N+1$  (Fig.10).

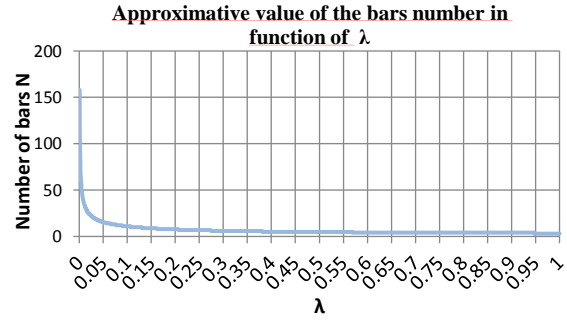


Figure 10 . Equation of the bar number

## 2.3 Folded configurations

According to the aimed initial compactness, bars can be packed in two different arrangements. In a first configuration, (Fig.11.a) bars are distributed along a circle, and deploys themselves in one phase (2D deployment). A second possibility is the case where bars are arranged on two concentric circles (Fig.11.b), which necessitate a two-phase deployment, as showed with numerical simulation in Fig.12.

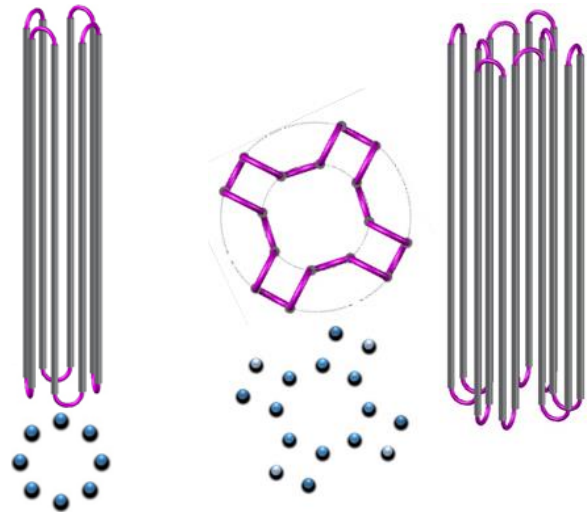


Fig.11.a

Fig.11.b

Figure 11 . Diverse disposition of the bars at the initial step

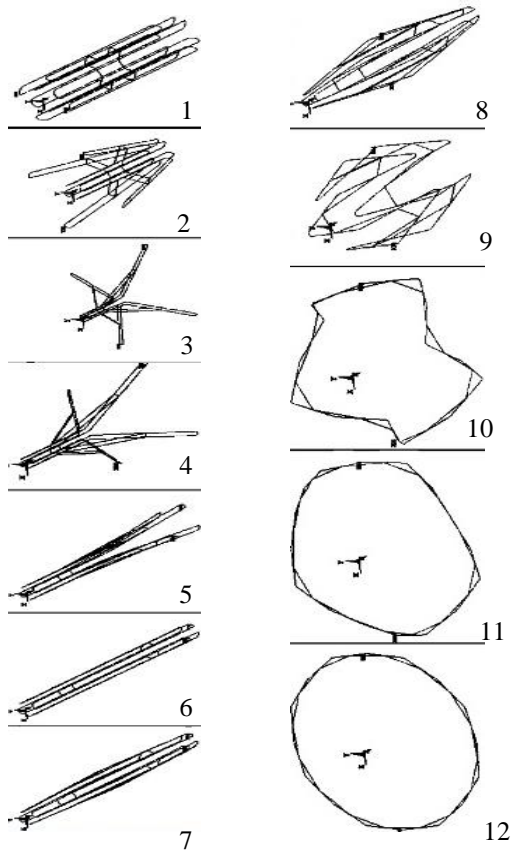


Figure 12 . Two stage of deployment for a 2 circle configuration

## 2.4 Physical model

A demonstrator of solar sail was built, with bars in glass fiber, steal compression springs and a 13  $\mu\text{m}$  thick Mylar sheet (Fig.13). It allowed testing the compactness and the folding of a complete set sail structure.



Figure 13 : Picture of the demonstrator for initial and final step

Another model made up of aluminum tubes and tension springs for connection was elaborated. Bars are 6mm diameter with a thickness of 1.5mm. Springs coming to insert into tubes are 3mm diameter, and are arranged so

that their length between two bars is of 1.4cm. We represent in (Fig.14) several pictures of our 8 bars structure. A crossing cable passing through the middle of the bars control the spread.



Figure 14 : Physical ring model

## 3. STATIC EQUILIBRIUM OF THE RING

### 3.1 Tetrahedron equilibrium

It is possible to calculate the bending moment in the connections as well as the tension presents in the thread to every step of the deployment. They depend at the same time on characteristics of materials and the geometry of considered aperture. For a given configuration, the static equilibrium is insured in Eq.5:

$$\frac{|M_{\text{joint}}|}{|F_c|} = \left[ \frac{1}{2} L_b + \frac{\pi R_{\text{init}}}{\pi - \alpha} \left( 1 - \sin\left(\frac{\alpha}{2}\right) \right) \right] \cos\left(\frac{\alpha}{2}\right) \quad (5)$$

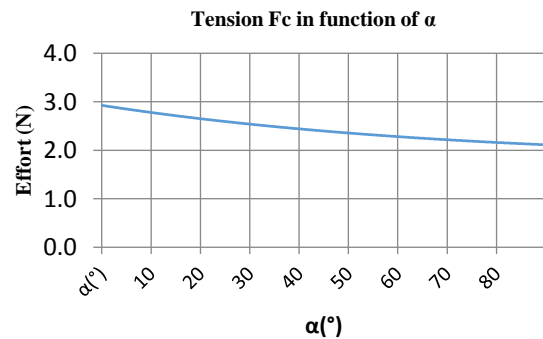


Figure 15 . Tension in the cable

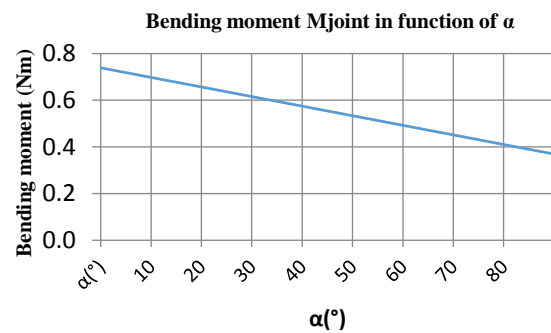


Figure 16 . Bending moment graphic

The effort on the cable is given by  $F_c$  in Eq.6:

$$F_c = \frac{E_{joint} I_{joint}}{R_{init}} \frac{\left(1 - \frac{\alpha}{\pi}\right)}{\left[\frac{L_b}{2} + \frac{\pi R_{init}}{\pi - \alpha} \left(1 - \sin\left(\frac{\alpha}{2}\right)\right)\right]} \cos\left(\frac{\alpha}{2}\right) \quad (6)$$

Where  $E_{joint}$  is the Young modulus of the joint and  $I_{joint}$  the moment of inertia of the joint. In the same way, we define the moment in the joint by Eq.7:

$$M_{joint} = \frac{E_{joint} I_{joint}}{R_{init}} \left(1 - \frac{\alpha}{\pi}\right) \quad (7)$$

As illustrated in Fig.15 and Fig.16,  $F_c$  and  $M_{joint}$  are decreasing in function of  $\alpha$ .

### 3.3 Comparison between our analytical model and Ansys model

Every bar is split into 8 elements of type " Beam4 ", cables by two elements of type" Link10 ", flexible connections by 20 elements of type " Beam4 ". The physicals and geometrical properties of the elements are showed in Tab.1. The mechanical evaluation for our model was made by ANSYS®. Many modeling were done with various numbers of bars for different  $\alpha$  angles. The obtained results are very satisfactory. Indeed, our error of modelling does not exceed 0.87 % (Tab.2).

	Geometry				Mechanicals properties		
	Length (cm)	Diameter (mm)	Thickness (mm)	Inertia moment (m <sup>4</sup> )	Density (kg/m <sup>3</sup> )	Poisson ratio	Young Modulus (N/m <sup>2</sup> )
tube	40	6	1.5	51.05 <sup>E-06</sup>	2700	0.346	2.10E+09
joint	2.5	3	-	0.042 <sup>E-12</sup>	7500	0.27	0.69E+09
cable	-	-	-	-	7500	0.3	125 <sup>E9</sup>

Table 1 . Modelisation of elements


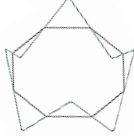



N	Geometries	$\alpha$	$L_c$	$F_c$	$F_c^{Ansys}$	$M_J$	$M_J^{Ansys}$	$\delta_F$	$\delta_M$
4		45 °	1.73E-1 m	2.593 N	2.610 N	0.495 Nm	0.499 Nm	0.65%	0.76%
8		60 °	2.21E-1 m	2.466 N	2.477 N	0.440 Nm	0.444 Nm	0.43%	0.87%
12		90 °	3.05E-1 m	2.279 N	2.277 N	0.330 Nm	0.333 Nm	0.11%	0.79%
16		120 °	3.70E-1 m	2.165 N	2.160 N	0.220 Nm	0.221 Nm	0.21%	0.67%
20		162 °	4.20E-1 m	2.098 N	2.092 N	0.066 Nm	0.066 Nm	0.30%	0.19%

Table 2 . Comparison between analytical and ANSYS results



#### 4. CONCLUSION

This paper presents a new kind of deployable structure. The assembly of several tetrahedrons form an auto-deployable structure which will be used as support plan of reflectors or solar panels.

A geometrical analysis was done on the tetrahedron. We calculate the optimal surface, volume and the length of the cable exactly. For a plane deployment, with a given surface, a length of bar fixed, an equation of the bar number is established. The presented static analytical model of the ring is very accurate.

Currently, a modal analysis of the ring is in progress. The equations of the dynamic of the deployment are performed. A study of a new cable net system is in progress to create a deployable parabolic reflector.

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